Mars Science Laboratory Entry Guidance

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Abstract—The Mars Science Laboratory will be the first Mars mission to attempt a guided entry with the objective of safely delivering the entry vehicle to a survivable parachute deploy state within 12.5 km of the pre-designated parachute deploy coordinates.

The Entry Terminal Point Controller guidance algorithm is derived from the final phase Apollo Command Module guidance and, like Apollo, modulates the bank angle to control range based on deviations in range, altitude rate, and drag acceleration from a reference trajectory. For application to Mars landers which must make use of the tenuous Martian atmosphere, it is critical to balance the lift of the vehicle to minimize the range while still ensuring a safe deploy altitude.

An overview of the process to generate optimized guidance settings is presented, discussing improvements made over the last nine years. Performance tradeoffs between ellipse size and deploy altitude will be presented, along with imposed constraints of entry acceleration and heating. Performance sensitivities to the bank reversal deadbands, heading alignment, attitude initialization error, and entry delivery errors are presented.

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1. INTRODUCTION

Previous Mars lander missions (fill in intro). The Mars Science Laboratory (MSL) will demonstrate improved landing accuracy using active onboard guidance in support of the landing accuracy requirements for future robotic and subsequent manned missions. The baseline mission design delivers a rover payload to the surface, using a direct-entry trajectory and a trimmed entry vehicle lift-to-drag ratio of 0.24. The goal of the MSL precision landing demonstration is to achieve parachute deployment within a 12.5 km horizontal radius of the nominal deployment target. Terminal phase deceleration will be accomplished by the parachutes, followed by powered descent to a soft landing using the skycrane.

The Entry Terminal Point Controller (ETPC) is derived from the Apollo command module entry guidance. This algorithm was competitively selected for use with the Mars 2001 lander, which later became the Mars *Phoenix* lander.[1] The Apollo guidance has been man-rated and successfully flight proven with the 0.3 L/D command module on entries from Earth orbit as well as direct lunar returns. A detailed development of all phases of the Apollo guidance algorithm and their application to Apollo Earth entry trajectories is presented in Reference #.

The objective of this paper is to present the modifications which have been made to adapt the ETPC algorithm for use with MSL. The processes for optimizing the entry guidance and trajectory for the best performance are discussed. The sensitivities influencing entry performance are identified.

Relevant Project Requirements

The project requires that the entry flight system to safely deploy the parachute within 12.5 km of the planned deploy target. Note that with wind dispersions, which are site dependent, this may translate to a larger ellipse on the ground. This deployment must occur in conditions that do not violate the parachute constraints and still allow sufficient time and altitude to complete the subsequent descent and landing tasks. Entry guidance must work in concert with the navigation and control systems to accomplish this.

Design Considerations

In addition to the project requirements and design principles, there are several considerations important to the design of the entry guidance. Understanding the atmosphere environment, what is predictable and what is not, is important for Mars landers. The entry guidance must be robust to handle the large uncertainties in the Martian

environment. These uncertainties are largely the result of very limited observational atmospheric data and the rapid atmosphere dynamics on Mars which make it challenging to forecast.# <ref atmo papers, Ashwin>

The selection of the landing site after the project Critical Design Review in 2007 means that the entry flight system has to meet the project requirements across a variety of landing site latitudes and arrival dates. These differences influence the entry speed, the local environment properties, and the navigation knowledge provided to the spacecraft prior to entry. The entry guidance must provide acceptable performance across this range.

The navigation system is only using IMU acceleration measurements during entry, with no other sensors to provide information on airspeed or to reduce the position knowledge error. Although the baselined IMU is substantially more accurate than those of previous Mars landers#, the entry guidance and parachute deploy trigger must rely on state estimates with these limitations. Even if the entry guidance were "perfect" in its performance, the deploy ellipse would be no smaller than that of the position uncertainty of the onboard navigation system.

Finally, the verification and validation of the entry guidance is crucial to the success of MSL. These tasks are made neasier by using simple and proven algorithms when possible, by designing so that the performance predictably degrades with larger dispersions, and by minimizing the complexity of the flight software. The performance of the entry guidance with expected dispersions and the robustness of the entry guidance to severe dispersions can be evaluated using 3- and 6- degree-of-freedom simulations#.

Relevant Terminology

The following terms are common to entry guidance design and analysis and may be unfamiliar to some readers.

"In-plane" describes a vector component that is contained within the radius-velocity state vector plane using a planet-fixed coordinate system. This plane's orientation changes slightly during entry. "Out-of-plane" describes a vector component that is normal to the same plane.

The term "downrange" describes the in-plane range from the entry vehicle to the target. The term "crossrange" describes the out-of-plane range from the vehicle to the target.

Define "bank angle", sign direction. <figure showing bank>

A "bank reversal" occurs when the sign of the commanded bank angle changes, indicating the bank direction of the vehicle should change from left to right or vice versa.

"Planet-Relative Velocity" refers to the surface-relative velocity magnitude, using a planet-fixed coordinate system. **Any velocity reference in this paper is using this definition, unless specifically defined as another.** Note that this velocity magnitude definition includes the vertical velocity component.

"Wind-relative velocity" refers to the airspeed of the entry vehicle, accounting for planetary rotation and the local wind and any vertical velocities.
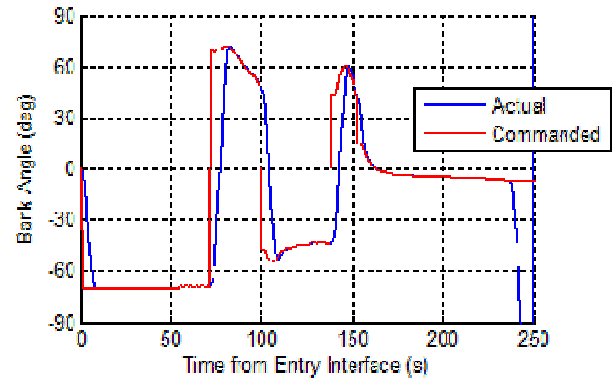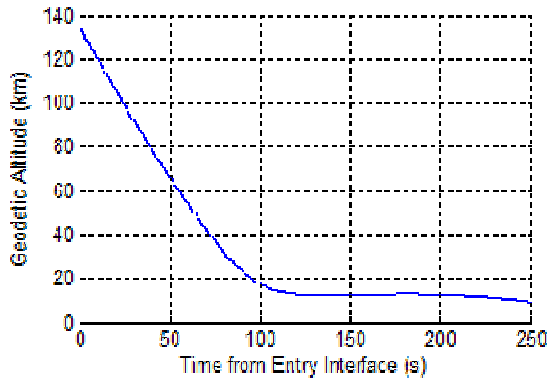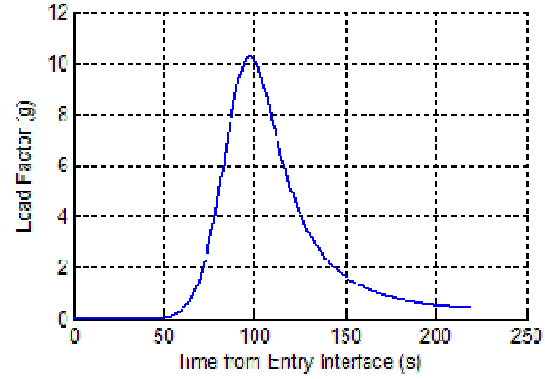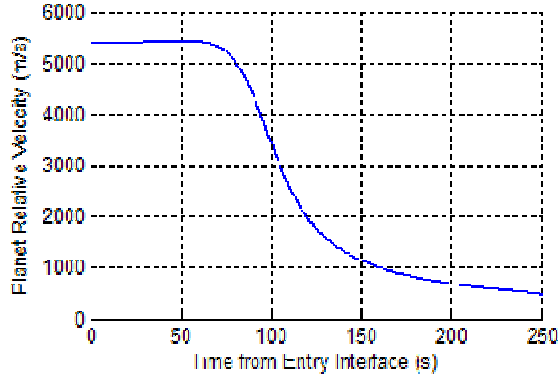
2. ENTRY GUIDANCE OVERVIEW

The entry guidance is divided into three distinct phases, discussed below in the order that they occur.

(1) Pre-bank. The entry capsule maneuvers into the pre-bank attitude minutes prior to entering the atmosphere. An angle-of-attack is commanded that is similar to the expected trim angle. The commanded bank angle is constant at a pre-bank value associated with the initial nominal bank angle. This is intended to reduce the propellant usage by attempting to begin atmospheric flight near the trim angle of attack and the first commanded bank angle expected.

(2) Range Control. Once the filtered drag acceleration magnitude climbs past 0.2g, the GNC flight software has determined that the vehicle has entered the sensible Martian atmosphere and begins range control. During this phase the entry guidance is predicting the downrange flown and commands a bank angle to correct for any range errors. Simultaneously, the guidance is monitoring the crossrange to the target and will command a bank reversal whenever the crossrange crosses a deadband threshold. This ensures that the crossrange, although not directly controlled, will be managed within a magnitude correctable during the next phase.

(3) Heading Alignment. Once the estimated velocity has dropped past 1100 m/s, the guidance ceases range control and begins heading alignment. The bank angle is commanded to steer the vehicle to fly towards the target deploy coordinates. By limiting the magnitude of the commanded bank angle to 15 degrees, it is ensured that most of the lift is countering gravity. This thereby increasing the parachute deploy altitude.

<table of phase, trigger, velocity, Mach, g-load, altitude>

Entry guidance ceases when the sequence of events leading to parachute deploy is commanded, starting with the first jettison of ballast as the vehicle begins to return to a trim angle-of-attack of zero just prior to parachute deploy.

Flight dynamics of the MSL entry trajectory plays a role in defining the latest sensible transition between range control and heading alignment. As the vehicle continues to decelerate during hypersonic flight, eventually it reaches a point where the lift acceleration can no longer counter the gravitational acceleration. This point is described as "equilibrium glide". This transition is important to guidance design as beyond this point, even if the vehicle was to command zero bank, it cannot increase the flight path angle to stretch the range flown and therefore has limited control of the downrange error at parachute deploy. However, the azimuth control is still effective at these lower speeds which allow the guidance to reduce the remaining crossrange error.

<plot of flight path and azimuth rate control>

3. RANGE CONTROL LOGIC

The original Apollo entry guidance design was designed for both low-orbit and lunar return. Sufficient mission flexibility was required to accommodate the large variations in entry conditions, including those of Earth orbit test flights and all types of lunar mission aborts. To satisfy target redesignation requirements for a weather alternate landing area, a high altitude controlled skip entry capability was included. The Apollo guidance algorithm was rated for human spaceflight and was successful on every Apollo mission.

For a direct Mars entry such as MSL, the skip control phases and switching logic are not used and only the final entry phase is incorporated into the range control phase. This algorithm controls to a terminal downrange and velocity target using pre-derived influence coefficients with respect to perturbations about an reference trajectory. This reference trajectory is defined by downrange from target, drag acceleration, and altitude rate as a function of velocity. The design of the reference trajectory is crucial to the success of the entry guidance for Mars entry applications and will be discussed later in this paper.

The predicted range-to-go (R_p) is calculated as a function of drag (D) and altitude rate (r-dot) errors with respect to the nominal reference trajectory profile, using equation 1.

$$R_p = R_{ref} + \frac{\partial R}{\partial D}\left(D - D_{ref}\right) - \frac{\partial R}{\partial \dot{r}}\left(\dot{r} - \dot{r}_{ref}\right) \qquad (1)$$

The desired vertical component of the lift-to-drag (L/D) ratio is calculated as a function of the difference between the actual and predicted range-to-go, i.e., the downrange error.

$$\left(\frac{L}{D}\right)_{V,C} = \left(\frac{L}{D}\right)_{V,ref} + \frac{K_3\left(R - R_p\right)}{\partial R/\partial(L/D)} \qquad (2)$$

The commanded bank angle (Φ_C) is then calculated as

3

$$\Phi_C = \cos^{-1}\left(\frac{L/D_{V,C}}{L/D}\right) * K2ROLL \qquad (3)$$

The partial derivatives of predicted downrange in equations 1 and 2 are the ETPC gains, which are derived using linear perturbation theory with the nominal reference trajectory by reverse integration of the differential equations adjoint to the linearized equations of motion. These gains are optimized for converging the flown trajectory to the reference trajectory by the final velocity are implemented in the guidance as tabular functions of velocity.

Because of slow system and trajectory responses to guidance commands, performance is empirically enhanced by the use of the over-control gain K_3 in equation 2 to improve range convergence behavior. The over-control gain also ensures the robustness of the range control algorithm for trajectory states sufficiently different from the reference trajectory that the linearized equations of motion may no longer be accurate.#

The sensed drag acceleration and lift-to-drag ratio (*D* in equation 1 and *L/D* in equation 3) are derived from accelerometer measurements and smoothed by first order filters. The term *K2ROLL* in equation 3 is the bank directional control (±1), which is reversed each time the target crossrange out of plane central angle exceeds the bank reversal criterion. The crossrange at which to command a bank reversal is a quadratic function of velocity.

ETPC Modifications

Notable modifications from the original Apollo final phase algorithm include:
(1) Variable bank reference profile. The original Apollo guidance, from which ETPC is derived, assumed a constant bank reference profile which resulted in a constant vertical L/D reference term in Equation 2. For Mars landers seeking to increase the deploy altitude, a variable bank profile is used to provide higher deploy altitudes while reserving range control authority at high speeds. This results in the vertical L/D reference term changing as a function of velocity. This provides more flexibility in trajectory design and has been critical to meeting the project requirements for MSL while the entry mass and ballistic coefficient has gradually increased.#

(2) Vertical L/D command limiter. Studies by A. D. Cianciolo# at NASA Langley Research Center demonstrated that the early algorithms of entry guidance may not be robust in the presence of unexpected, large density shears that occur in the altitudes during which the vehicle flies with a flight path angle close to zero, such as late in range control and throughout heading alignment. Such shears have been observed in many Shuttle flights at Earth in atmospheric densities comparable to those MSL will fly within at Mars.# These shears resulted in increases in the deploy ellipse size and several kilometers loss in altitude. It is expected that severe wind shears may result in similar behavior. To reduce the responsiveness of the entry guidance to such severe dispersions, a vertical L/D command limiter has been implemented. The details will be explained in a later section.

It is the opinion of the authors that these modifications improve the robustness of the system without significantly altering the algorithm such that its heritage cannot be traced back to Apollo.

4. BANK REVERSAL LOGIC

As mentioned before, bank reversals are triggered during the range control phase when the magnitude of the target crossrange exceeds the reversal criterion. This criterion is described as a quadratic function of velocity. Dispersions in atmospheric density or the vehicle aerodynamics can result in bank angle commands which remain near or saturated at maximum or minimum limits for a significant length of time, slowing the crossrange error rate. Such behavior also alters the speeds and times at which bank reversals occur.

The original Apollo guidance utilized only a single crossrange corridor. However, as a result of the larger atmospheric density variations of Mars, a tighter crossrange corridor was added for the first bank reversal, which provides improved performance by minimizing the peak crossrange overshoot that occurs after the first reversal. The corridor width is increased to the second level when the first reversal is initiated as shown in figure 3. Minimum bank angle command limits are implemented to maintain adequate crossrange control capability when the vertical L/D commands are saturated. The minimum bank limit is normally 15 degrees, which preserves adequate crossrange control in dispersed cases.
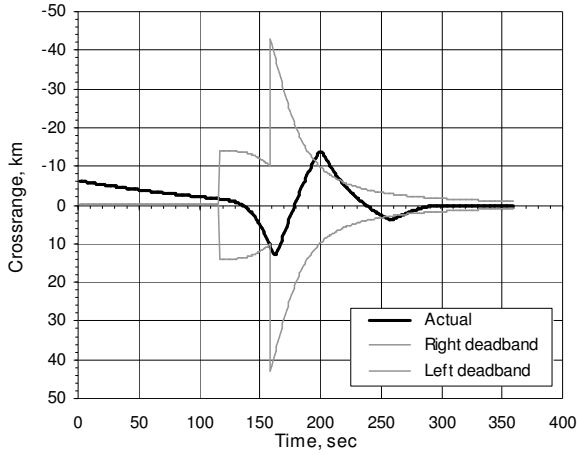
Figure 1: Sample bank reversal corridors.

5. HEADING ALIGNMENT LOGIC

When the velocity becomes less than approximately 1100 m/s, the effectiveness of bank angle modulation in controlling downtrack errors becomes significantly diminished. At this point the bank commands are switched to a heading alignment controller instead, which aligns the vehicle velocity heading with the target, nulling the crossrange error when the target is reached.

The commanded bank angle is proportional to the current azimuth error to the target, defined by the crossrange, R_c, and downrange, R, to the target as shown in equation 4.

$$\Phi_C = \tan^{-1}\left(\frac{R_c}{R}\right) \qquad (4)$$

As mentioned, the commanded bank angle is not allowed to return a value greater than 15 degrees magnitude in this phase in order to increase the deploy altitude while still allowing some reduction of crossrange error.

6. REFERENCE TRAJECTORY DESIGN

The primary objective of the guidance design is to achieve the best horizontal position accuracy possible with respect to the desired parachute deploy target while remaining within the constraining criteria of parachute deploy altitude, mach, and dynamic presusre. As the landing site has not been selected, the guidance is also designed to achieve the highest deployment altitude for a given vehicle configuration, entry interface, and atmosphere conditions. The reference profile design process uses optimal bank shaping to achieve these requirements.

Deployment Constraints

Constraints on the parachute deployment conditions directly affect the guidance design in order to ensure adequate margins for the dispersed trajectories to meet performance requirements.

Deployment Altitude. MSL uses a propulsive descent system after parachute deceleration. There is a timeline margin requirement, allowing sufficient time to be spent on the parachute, on the radar, and on the powered descent to land safely. This timeline is often translated into a minimum chute deployment altitude relative to the surface, below which the chute and propulsive system cannot decelerate the lander in time for a soft landing. The minimum altitude is a function of propulsive acceleration, the greatest expected altitude rate at chute deployment, and the chute drag acceleration. For MSL, the minimum dispersed deployment altitude above the ground has been determined to be 4.0 km.

Mach Number. The Mach number at chute deployment has two effects on the chute: aeroheating and inflation dynamics. If the Mach number is too high, the chute may fail due to excessive heating at the stagnation point or experience a violent inflation that excessively loads the chute. Inflation at transonic speeds is also usually an area of concern. For MSL which is using a parachute with *Viking* heritage, the deploy Mach limits are 1.1 to 2.2.

Dynamic Pressure. Sufficient dynamic pressure at chute deployment is critical to ensuring inflation. If the dynamic pressure is too low, the chute may have difficulty inflating properly. If the dynamic pressure is too great, the resulting peak inflation loads may cause the chute to fail. For MSL which is using a parachute with *Viking* heritage, the selected dynamic pressure limits are 250 to 850 Pa.

A parachute deploy logic studied during MSL conceptual design was termed the "smart chute" logic, which sought to achieve the least possible range to the target while remaining within the deployment constraints. An acceptable range of deploy velocities and drag accelerations are defined, which approximate the Mach and dynamic pressure constraints as estimates of those parameters are not available. As long as the vehicle is within these acceptable ranges, the "smart chute" logic seeks to minimize the range to target. Whenever a minimum constraint limit is reached, the deploy is triggered regardless of the range. If the minimum range is reached but any of the constraints are exceeding the maximum limit, deploy is delayed until all constrainst are met.

Presently the baseline deploy trigger is a fixed velocity value, set just below Mach 2.2 which results in the chute deploying as soon as the onboard estimates shows it has slowed enough. This results in the earliest chute deploy possible, thereby raising the deploy altitude. For elevation

sites that are very low where deploy altitude is no longer as critical, MSL may use the "smart chute" trigger given sufficient confidence in the descent timeline margin and deploy trigger.

Trajectory Constraints

These constraints are or will be placed on the entry trajectory design.

Acceleration Loads. The entry vehicle structure is rated up to 15g. The nominal acceleration load must be less than 13g so that the dispersed acceleration loads are less than 15g. Acceleration loads are primarily affected by the entry flight path angle. The bank profile during range control has a second-order effect on acceleration loads.

Heating. For the PICA heatshield, there is not yet a heat rate and heat load requirement for the entry trajectory. It is expected that this guidance algorithm will be able to accommodate these constraints when they are available. The heating

Communication Link. To provide limited real-time telemetry during entry, the trajectory must be timed to coincide with an orbital pass by one of the operational Mars program orbiters. The initial pre-bank direction, left or right, may be chosen so to increase the time of the communications link.

Profile Shaping

The shaping of the nominal reference profile for the MSL preliminary design must meet three requirements. It must minimize the horizontal range error at chute deployment with the 3-sigma dispersed runs deploying within 12.5 km of the target latitude and longitude. The vehicle must reach the target ellipse when the chute deploy sequence is triggered. Otherwise the deployment constraints may force an early or late deployment, negatively impacting the range error. Designing the nominal profile to perform acceptably in dispersed cases is of prime importance. Finally, as the MSL has no selected landing site, the chute deployment altitude capability must be maximized in order to permit landings over much of the surface of Mars.

Since ETPC guidance controls within a corridor about the reference profile to converge the terminal range, it is desirable to design this profile to provide as much margin as possible from the vehicle maneuver capability limits to accommodate dispersions. This means that bank angles of the nominal reference trajectory should allow sufficient margin so that, in a dispersed simulation, the guidance and vehicle is able to retain sufficient capability to converge the range without sustained bank angle saturation.

The shaping of the reference profile is done in an open-loop simulation with a bank angle profile that varies as a function of velocity. This profile varies generally is of the shape of bank angles between 60 and 90 degrees at high speeds and linearly ramp down an angle between 40 and 50 degrees bank angle at slower speeds to prolong the time spent in the lower, more dense atmosphere and raise the deploy altitude. Optimizing the variable bank profile is somewhat involved as there are several variables to manipulate.

During MSL conceptual design phase, a design guideline of using reference trajectories with maximum altitude rates near zero was employed. This prevented excessive lofting in the trajectories and ensured that the guidance would rarely saturate and maximizing the deploy altitude. As the ballistic coefficient has increased as the entry vehicle and rover design matures, this guideline has been replaced with a guidance saturation limit during the range control phase of some selected stress cases.

A simple variable bank profile that has performed well is a linear ramp between two constant values, such as shown in **Error! Reference source not found.**. Investigation has shown that most acceptable variable bank profiles begin with a low-vertical lift bank angle, usually between 60° and 80°. The nominal bank angle then decreases to the minimum bank angle found in Equation 4, typically close to 45°. The variable bank profile requires deployment constraint margins that are similar to those of the constant bank profile.

When an acceptable bank profile is found, controller gains are then derived from the resulting reference trajectory. The closed loop performance of the nominal and dispersed trajectories is assessed to determine if another iteration of optimizing the bank profile is required. Changes to the guidance gains and lateral control logic may also provide improved performance. Figure 2 is an example of dispersed performance for an optimized reference profile for a landing site at 2.5 km elevation. The robustness of the guidance is demonstrated as all of the dispersed deployments occurred within 5 km of the target, within the deployment constraints.

7. GUIDANCE PARAMETER DESIGN

In additional to the guidance gains generated by the reference trajectory, there are also a number of key parameters that influence the entry performance.

Pre-Bank Angle

The pre-bank angle is the bank angle maintained by the vehicle as it passes entry interface until entry guidance is activated. If the pre-bank angle is more than several degrees off from the first guided entry bank command, it results in large attitude maneuver that is not propellant efficient.

When the estimated vehicle delivery state to atmospheric entry is known to differ from the reference trajectory while easily remaining within the performance capability of the vehicle, the pre-bank angle can be easily tuned to minimize this initial bank maneuvering. This delivery error sets the magnitude of the pre-bank angle. The sign of the pre-bank angle, whether the vehicle banks left or right as it enters the atmosphere, is driven by communication constraints.

<include plot of how delivery error influences pre-bank angle>

Vertical L/D Command Limiter

MSL GNC investigated the inclusion of a vertical lift-vs-drag (L/D) command limiter, or "Safety Net", into the flight software algorithm to provide reasonable limits on the controller Gemini had a similar constraint in that it prevented any negative vertical L/D commanded (i.e., some lift-down) to prevent excessive g-loading of the crew.
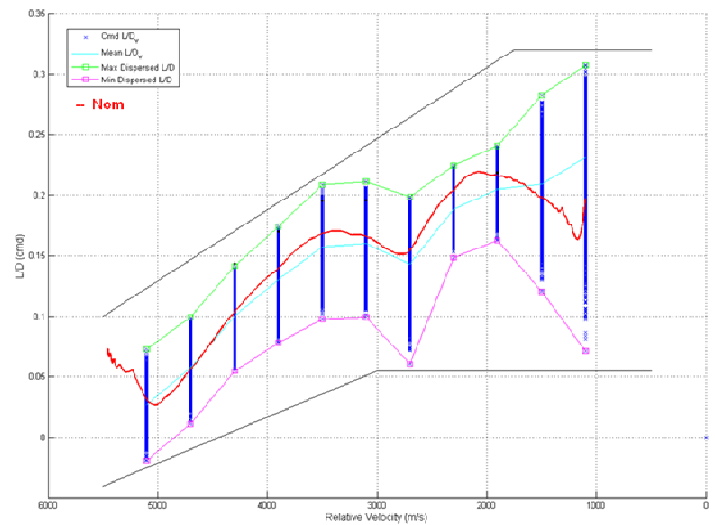
These limits are tighter than full lift-up or full lift-down, whereby the controller is bound to a relatively small range of L/D. Setting these boundaries in the controller should not impact the performance of the nominal trajectory, but yet potentially save some extreme trajectory stress cases, such as those with high density shears, aerodynamic torques, and dust tau (as seen during dust storm activity).

In order to select the vertical L/D command boundaries for the entry guidance controller, a baseline 8000 case Monte Carlo was run utilizing POST2 v4.2 and the 3-DOF MarsGRAM point design for the 09-EBW-01 trajectory. The large Monte Carlo sample assures that a wide range of dispersions are accounted for in considering the L/D limits and thus provides a basis for defining the minimum and maximum commanded L/D values possible during MSL Entry-Descent-Landing (EDL). From this Monte Carlo, individual extreme cases were selected for analysis, based upon a minimum survivable chute-deploy altitude of 5.5 km (Case #1953) and a maximum acceptable chute-deploy range error of +/- 10 km (Case #406). As it is desirable to implement the simplest scheme possible into the flight software to avoid unnecessary complications and errors during real-time operations, it was determined that a linear boundary could be utilized as a function of velocity at 3 points along the trajectory (near entry, middle, and around heading alignment). A parametric sweep was performed to better optimize the commanded L/D at an associated velocity independently for both the minimum and maximum boundaries.

The algorithm was modified to include this vertical L/D command limiter as a look-up table and forcing the range control algorithm to utilize these L/D limits should the controller calculate commanded L/D values greater or less than those boundaries. The aforementioned extreme

trajectory cases were run with the parametrically varying L/D limits from the reference gain table, followed by evaluating the deploy altitude and downrange output. Based upon these results, a near optimal minimum and maximum vertical L/D command vs velocity profile was then chosen. To test the robustness of these chosen boundaries, 1000-case Monte Carlos were run for extreme stress cases, such as a large range-bias (+/-1000 km) which would force the controller to ride the commanded L/D limits. 1000-case Monte Carlos were also run for stress cases of +/-30% density shear, and dust-tau of 0.9, respectively.

Figure 1 depicts the range of vertical L/D commanded values vs velocity for an 8000-case baseline Monte Carlo and the conceptual minimum and maximum vertical L/D limits implemented.

The results show that the vertical L/D command limiter does not affect the performance of the baseline trajectory, which is as desired. For extreme cases, the limiter allows for about 97% of cases which fall far downrange (-1000 km range bias) of the landing target to be saved. Additionally, while all unlimited L/D extreme uprange (+1000 km range bias) trajectories fail due to high mach number at chute deploy, the inclusion of the Safety Net allows for about 9% of those cases to successfully reach chute deploy, with 21% of cases reaching a deploy altitude greater than 5 km. For +/-30% density shear, the L/D Safety Net decreases range error while increasing deploy altitude by as much as 800m. It was found that the extreme dust tau case of 0.9 is already survivable and that the application of L/D boundaries did not impact performance.

Based upon these findings, it was decided that the vertical L/D command limiter will be implemented into the flight software. Future work may include further refining of the Safety Net boundary profile and the strategy which it will be

implemented during EDL.

8. GUIDANCE PERFORMANCE SENSITIVITIES

It is possible, for a particular vehicle configuration in a given atmosphere defined by time and location, that the dispersed entry performance will not be acceptable for any combination of bank profile or guidance tuning. Such a situation usually leads to reassessment of the deployment constraints, the vehicle configuration (particularly ballistic coefficient), and selecting a date or site with more favorable atmospheric conditions.

Vehicle Configuration

Two parameters of the vehicle configuration play an important role in the design and performance of the entry guidance. Reference 3 discusses some approximate relationships between deployment conditions and vehicle configurations.

Ballistic Coefficient. The maximum acceptable ballistic coefficient of a vehicle configuration is dependent on the atmospheric conditions near the landing site. The greater the ballistic coefficient, the less drag acceleration experienced prior to chute deployment. If the ballistic coefficient is too great, the vehicle will not be able to decelerate in time to meet the chute or altitude deployment constraints. Lowering the ballistic coefficient allows a higher density altitude deployment at the cost of a lower dynamic pressure and higher Mach numbers due to the lower atmosphere density and temperatures. Figure 5 shows how the deployment conditions in Mach, dynamic pressure, and altitude can vary as a function of ballistic coefficient for constant-bank open-loop trajectories optimized to maximize the nominal deployment altitude using a 0.24 L/D configuration. The atmosphere data was generated by MarsGRAM 2001 for a late winter arrival in the southern hemisphere[4].
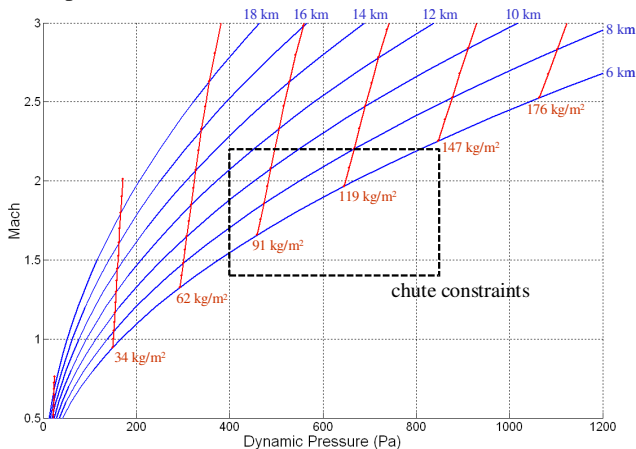
Figure 5: Sample optimized, constant-bank reference trajectories of different ballistic coefficients.

Lift-to-Drag Ratio. The minimum required L/D of a vehicle

configuration is dependent on the desired deployment altitude as well as dispersions and uncertainties of the atmosphere, aerodynamic properties, and entry flight path angle. The greater the flight path angle dispersions are, the greater the possible delivery range error that the guidance must correct for. A greater L/D configuration is then required to 'fly out' larger delivery range errors. However, a greater L/D also has the undesirable effect of diverging the range error during bank reversals – too much L/D will diverge the range error during a reversal beyond recovery.

Atmospheric Conditions

The performance of the vehicle is heavily dependent on the atmosphere conditions of Mars, which vary in time and surface location. The chute deployment constraints of dynamic pressure and Mach number are directly related to the densities and speeds of sound in a given atmosphere profile. Due to this relationship, it is possible to determine the altitude and velocity for a particular Mach number and dynamic pressure in an atmosphere profile. By selecting a nominal chute deployment Mach and dynamic pressure it is possible to compare deployment altitudes between different atmosphere profiles. Since minimum deployment altitude is another constraint, the nominal deployment altitude is a useful figure of merit in estimating 'when' and 'where' the best opportunities for landing on Mars may be. This assumes the vehicle configuration allows the desired deployment conditions to be achieved.

Entry Date. The atmosphere of Mars varies greatly over the Martian year due to trends in the atmosphere related to the hemisphere seasons, distance from the sun, and the subliming and freezing of the atmosphere at the polar ice caps[5]. Solar longitude (L_s) is used as a standard of defining periods and seasons in the year. An L_s of 0° is the equinox of the northern hemisphere and an L_s of 90° is the summer solstice of the northern hemisphere. The average dust tau, a measure of the opacity in the atmosphere, also varies depending on the L_s and contributes to variations in atmospheric profiles.

Landing Site. The seasonal effects on the atmosphere are more pronounced for sites at higher latitudes. Some atmospheric models of Mars also take into account terrain effects which can vary the atmosphere properties as a function of longitude.

Figure 6 illustrates how the nominal deployment altitudes above the geoid can vary depending on the L_s and latitude, using the atmospheric model MarsGRAM 2001[4]. The nominal deployment conditions were selected to be Mach 2.0 and a dynamic pressure of 600 Pa. These preliminary results indicate that the higher latitudes are best reached during their spring and summer seasons. The low latitude sites are most accessible when Mars is near its perihelion (L_s of 250°). Missions to high elevation sites may be inhibited by entry date due to the atmospheric conditions and chute

constraints that the vehicle can simply not perform acceptably within. This will also limit lander missions that do not perform precision landing.

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